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IN-FLIGHT SIMULATION STUDIES AT THE NASA DRYDEN FLIGHT RESEARCH FACILITY

MARY F. SHAFER

Dryden Flight Research Facility
Edwards, California

SUMMARY

Since the late 1950s the National Aeronautics and Space Administration's Dryden Flight Research Facility has found in-flight simulation to be an invaluable tool. In-flight simulation has been used to address a wide variety of flying qualities questions, including low-lift-to-drag ratio approach characteristics for vehicles like the X-15, the lifting bodies, and the Space Shuttle; the effects of time delays on controllability of aircraft with digital flight-control systems, the causes and cures of pilot-induced oscillation in a variety of aircraft, and flight-control systems for such diverse aircraft as the X-15 and the X-29. In-flight simulation has also been used to anticipate problems and to avoid them and to solve problems once they appear.

This paper presents an account of the in-flight simulation at the Dryden Flight Research Facility and some discussion. An extensive bibliography is included.

NOMENCLATURE

C^*	blended normal acceleration, pitch rate, and pitch acceleration
DFBW	digital fly-by-wire
DFRF	Dryden Flight Research Facility, Edwards, CA
FCS	flight-control system
GPAS	General Purpose Airborne Simulator
HUD	head-up display
L/D	lift-to-drag ratio
LLRV	Lunar Landing Research Vehicle
NASA	National Aeronautics and Space Administration
NASP	National AeroSpace Plane
PIO	pilot-induced oscillation
RAV	remotely augmented vehicle
RPRV	remotely piloted research vehicle
SST	Supersonic Transport
TIFS	Total In-Flight Simulator
USAF	United States Air Force
VSA	variable-stability aircraft
$1/\tau_{\theta_2}$	high-frequency pitch attitude zero
$\dot{\beta}$	sideslip rate, deg/sec
$\omega_{n_{sp}}$	undamped natural frequency of the short period mode, rad/sec

INTRODUCTION

Before flying an experimental aircraft it is always desirable to consider the flying qualities of the vehicle. If the new vehicle is similar to an existing aircraft, this may provide an idea of the flying qualities of the new vehicle. New aircraft of unusual configuration or flight envelope, however, require special handling.

Ground-based simulation is a good tool to use for an initial examination of the flying qualities, but ground-based simulators are deficient when reproducing visual or motion cues. They are suitable for many regions in the envelope, like cruise, but more demanding tasks, such as precision landings, frequently cannot be simulated well enough to provide complete confidence.

In-flight simulation does not have the same limitations as ground-based simulation. Visual cues are identical with those in the subject aircraft and motion cues, if the simulation is modeled correctly, also match those of the subject aircraft. In-flight simulation is also better at exposing deficiencies like proneness to pilot-induced oscillation (PIO). In fixed-base simulations, PIOs are not often seen, no matter how deficient the aircraft and its flight-control system (FCS), unless unusual, unrepresentative tasks are used. During in-flight simulation, these PIOs occur more readily.

There are two roles for in-flight simulation. The more difficult role is the examination of the dynamic response of an aircraft. Simulating the dynamic response (natural frequency and damping and the phasing between them, for example) of the subject aircraft requires modifying the dynamic response of the simulation aircraft. The variable stability aircraft used for dynamic simulation are the aircraft most often thought of when considering in-flight simulation.

The other role of in-flight simulation is performance simulation. This is the use of a similar aircraft to explore various performance characteristics which are not highly dynamic. An example of performance simulation is the use of an F-104 Starfighter in a low-lift-to-drag ratio (L/D) configuration to simulate the X-15 aircraft in approach and landing. No modification to the F-104 aircraft was required for this simulation, because the F-104 can easily be configured with low L/D.

In-flight simulation is more difficult, more time-consuming, and frequently more expensive than ground-based simulation and is reserved for those portions of the flight regime that cannot be adequately evaluated on the ground. It is not a cure all, as the simulation is only as good as the understanding of the characteristics of the simulated aircraft. The limitations of the simulator aircraft also limit the fidelity of the simulation.

The mission of the National Aeronautics and Space Administration's Dryden Flight Research Facility (NASA DFRF) is the study and flight test of a variety of unconventional and experimental fixed-wing aircraft. Dryden has used in-flight simulation to support this mission since the late 1950s. The first simulation was a generic study into the approach and landing of low-L/D aircraft using an F-104. The most recent was a 1990 inquiry into the visibility requirements in the approach and landing of a hypersonic vehicle using an F-104 aircraft.

Between these two simulations there have been a wide variety of simulation programs, using both dynamic and performance simulators to simulate such diverse subject aircraft as the X-15, the lifting bodies, the X-20 DynaSoar, and the X-29. Extensive inquiries into a variety of flying qualities topics have also been made. In keeping with the limitations of in-flight simulation, only pertinent portions of the flight regimes of the various aircraft have been studied.

This paper, a history of in-flight simulation at DFRF, describes the dynamic flight simulators and many of the performance simulators and presents a brief chronology of in-flight simulation here. The summary discusses a number of common threads in the history. An extensive bibliography is provided for further information.

DESCRIPTION OF SIMULATOR AIRCRAFT

There are two types of in-flight simulation, dynamic and performance, and, hence, two types of simulators. The dynamic simulator aircraft are extensively modified because control of the dynamic response is difficult. Computers control the actual response, completely overpowering the natural response of the aircraft. This complexity also means that these simulators provide the most information about flying qualities because they can be made to fly like different aircraft. In addition, the more recent of these variable-stability aircraft can be used to assess a variety of FCSs because the aircraft already have powerful and flexible flight-control computers.

The aircraft used for the in-flight simulation of the performance of the subject aircraft are much simpler. Typically, modifications are small changes to existing structures—a bigger speed brake, for example, to match the L/D of the subject aircraft better. These performance simulators are frequently used to provide information about the feasibility of a flight task, to provide qualitative information about a generic class of aircraft, or to establish piloting techniques. At the DFRF, the performance simulators were frequently support aircraft, pressed into duty when the need arose. This is particularly conspicuous in some of the visibility studies, where card or plastic was used to block the windows of standard support aircraft.

Performance simulation is less versatile than dynamic simulation because it is limited by the performance of the simulator aircraft. For example, the unmodified F-104 aircraft was not suitable for simulating the X-15 in any other flight regime, but it was an excellent simulator in the pattern.

Dynamic Simulators

Variable-Stability F-100C Super Sabre– The NASA F-100C Super Sabre (fig. 1), a single-engine swept-wing supersonic fighter, was modified by the Ames Research Center as a variable-stability research vehicle that provided variation of parameters around all three axes (refs. 1 and 2). An analog fly-by-wire

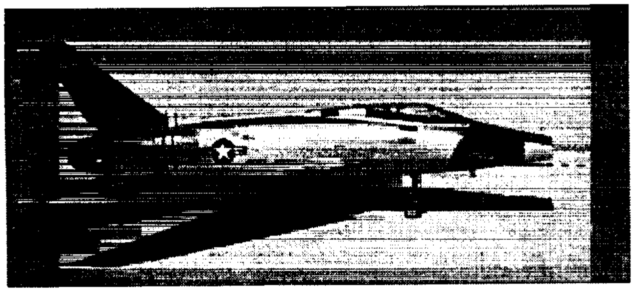


Figure 1. The NASA F-100 Super Sabre aircraft.

system was used in all three axes, although the pitch axis had safety trips installed because of the run-away potential of the all-moving horizontal tail.

NT-33A Variable Stability Aircraft– The United States Air Force NT-33A variable stability aircraft (VSA) (fig. 2) is an extensively modified T-33A Shooting Star jet trainer (ref. 3). The most conspicuous modification is the enlarged nose section that provides more room for electronics. The front seat, where the evaluation pilot sits, has a standard center stick or side stick and rudder pedal arrangement. The standard front seat control system has been replaced by a full-authority fly-by-wire FCS and a variable-response artificial feel system. The safety pilot sits in the rear seat to program the configuration characteristics.

The NT-33A aircraft has independent control of three-degrees-of-freedom for in-flight simulation. The simulation technique uses a response feedback methodology with three moment controllers of the vehicle (elevator, aileron, and rudder) as the simulation effectors. At one time the NT-33A had drag modulation, using drag petals at the wingtips, but this feature was removed following a structural failure.

The General Purpose Airborne Simulator– The NASA General Purpose Airborne Simulator (GPAS) (fig. 3) was a modified Jetstar, an executive transport airplane. The original modifications made the GPAS a four-axis simulator (pitch, roll, yaw, and

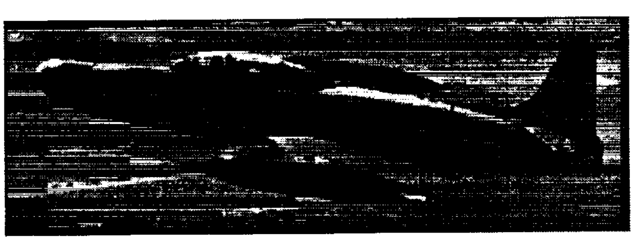


Figure 2. The USAF NT-33A variable stability aircraft.

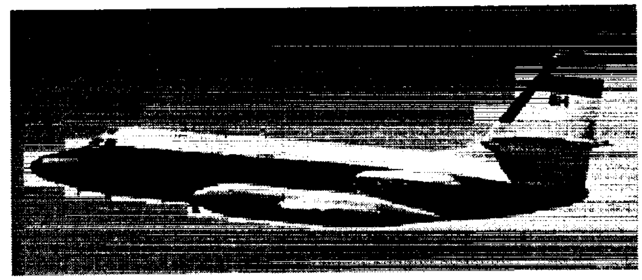


Figure 3. The NASA General Purpose Airborne Simulator aircraft.

thrust force along the longitudinal axis) with a model-following variable stability system (refs. 4 and 5). Direct lift control and direct side force were eventually added. The evaluation pilot sat in the left seat, which had a special set of transport-airplane-type controls and displays. This simulator exhibited extraordinarily good model following and had remarkable fidelity (ref. 6). Werner von Braun was taken for a demonstration flight early in the career of the GPAS. Impressed, he described it as a "dial-a-plane," the first known use of this phrase (ref. 6).

The Total In-Flight Simulator– The USAF Total In-Flight Simulator (TIFS) is a highly modified C-131 aircraft configured as a six-degree-of-freedom simulator (fig. 4). It has a separate evaluation cockpit forward and below the normal C-131 cockpit. The six-degrees-of-freedom are independently controlled by use of the elevator, aileron, rudder, throttle, direct lift flap, and side force surfaces. This side force surface is a large vertical surface mounted at mid-span of the wing. Longitudinal and lateral–directional model-following systems provide the evaluation pilot with motion and visual cues representative of the simulated aircraft. The evaluation cockpit can be modified with appropriate controls and displays and can accommodate a co-pilot. The TIFS can simulate turbulence and crosswinds or cancel an actual crosswind.

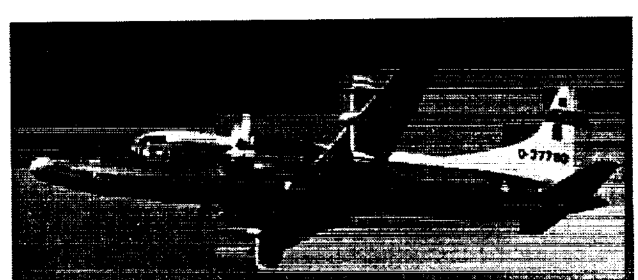


Figure 4. The USAF Total In-Flight Simulator aircraft.

The F-8 Digital Fly-By-Wire Aircraft– The NASA F-8 digital fly-by-wire (DFBW) was an F-8C Crusader, a single-engine, single-seat supersonic fighter (fig. 5), with a full-authority digital fly-by-wire FCS (ref. 7). The control system was designed so parameters such as time delays and control system gains could be entered from the cockpit in flight.

The aircraft was also capable of accepting control-surface commands from a ground-based computer when in the remotely augmented vehicle (RAV) mode (refs. 8–10). Using this feature, experimental control laws could be programmed in the ground-based computer, giving a special flexibility to simulation programs and keeping the evaluation pilot from knowing what configuration was being flown.

Calspan Variable-Stability Learjets– The Calspan variable-stability Learjets (figs. 6(a) and 6(b)) are executive transport aircraft, modified as three-axis simulators with a response feedback flight-control system (ref. 11). The evaluation pilot sits in the right seat, which is equipped with a center and a side stick which are, like the rudder pedals, driven by the variable feel system.

The first of these aircraft, a Lear 24D, was originally converted as a training tool for the Air Force and Navy test pilot schools, but has been used by DFRF for flying qualities research. It was converted to a variable-stability aircraft in 1981. The second, a Lear 25B, is used for flying qualities research. It was converted to a variable-stability aircraft in 1991. The two differ slightly; the second Learjet is larger and carries a bigger fuel load. It also has a programmable side stick, rather than the unmodifiable side stick in the first Learjet. A reprogrammable digital flight-control computer will be installed in the near future.

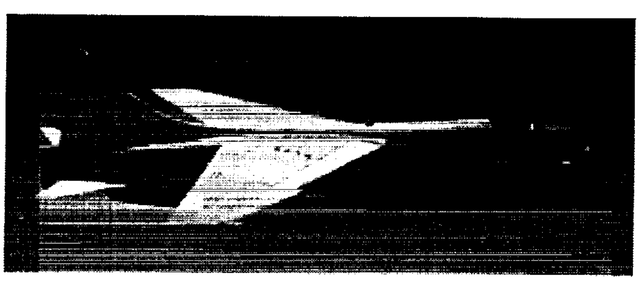
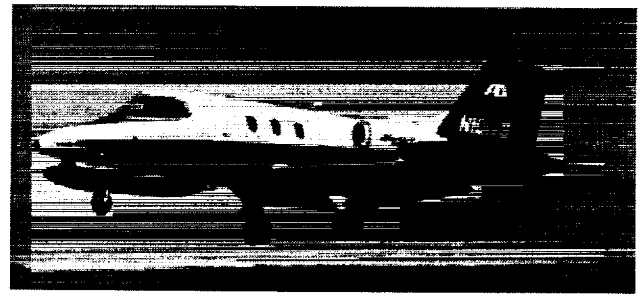
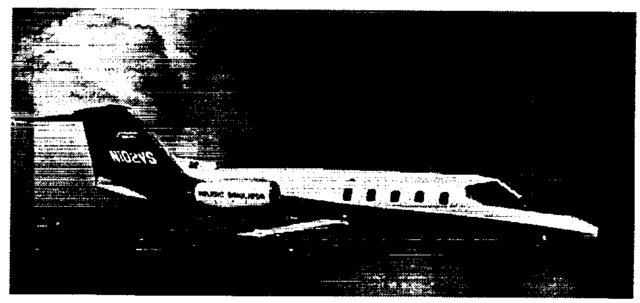


Figure 5. The NASA F-8 digital fly-by-wire aircraft.



(a) First Calspan variable-stability Learjet



(b) Second Calspan variable-stability Learjet.

Figure 6. Calspan variable-stability Learjets.

Performance Simulators

The aircraft used in performance simulators are not extensively modified. Most of these aircraft were used for support at DFRF.

The F-102A Delta Dagger– The NASA F-102A Delta Dagger was a single-engine supersonic delta-wing interceptor aircraft (fig. 7) that could be configured as a low-L/D aircraft in the power approach configuration (refs. 2 and 12). The F-102A Delta Dagger was used for pilot proficiency, chase, and research studies. It was modified with a larger speed brake for certain low-L/D aircraft studies.

The F-104 Starfighter– The NASA F-104 Starfighter is a single-engine, Mach 2 aircraft with a small, straight wing and a T-tail (ref. 2). The wing area is less than 200 ft^2 and the weight is approximately 24,000 lb, so it has a fairly high wingloading (ref. 13). These F-104 Starfighters were used for pilot proficiency, chase, and as testbeds for a variety of experiments. The F-104B and TF-104G (fig. 8), both

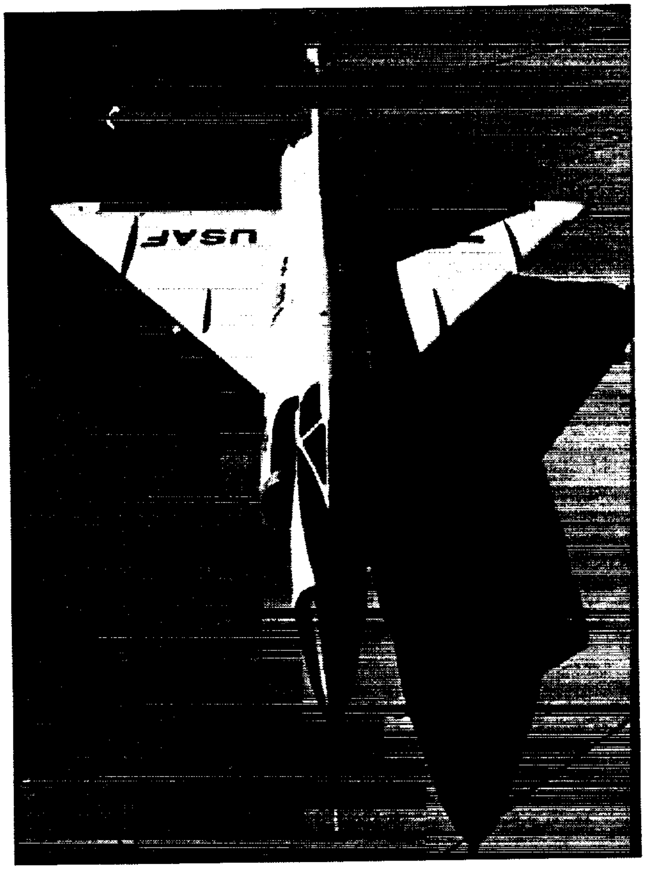


Figure 7. The NASA F-102A Delta Dagger aircraft.

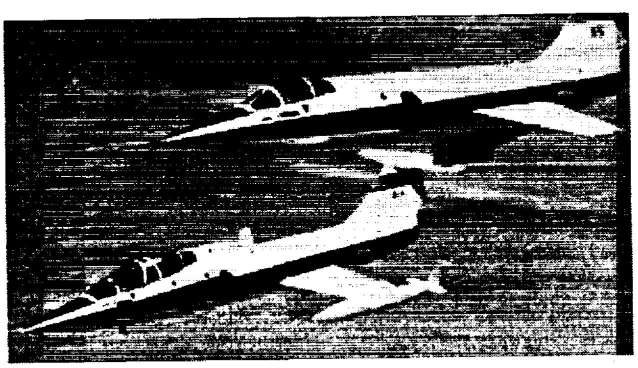


Figure 8. The NASA TF-104G Starfighter aircraft, lower left.

two-seat Starfighter aircraft, were used in restricted visibility studies. Another Starfighter, the YF-104A, was modified with a reaction control system.

The F5D Skylancer– The NASA F5D Skylancer aircraft (fig. 9) was designed as a carrier-based short range interceptor fighter (ref. 14). It was a tailless single-engine aircraft with a swept back wing of extremely low aspect ratio; the planform resembling

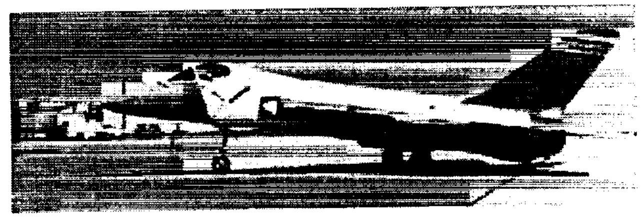


Figure 9. The NASA F5D Skylancer aircraft.

the proposed DynaSoar vehicle and some Supersonic Transport (SST) configurations. Enlarged speed brakes were used in a lifting body approach and landing study.

The A-5A Vigilante– The twin-engine supersonic strategic bomber A-5A Vigilante (fig. 10), operated by NASA, had a high wing, a rolling tail, and a slab fin (ref. 14). The low-aspect-ratio swept back wing had no ailerons; blown flaps were used for low speeds and spoilers and rolling tail for high speeds. The aircraft also had variable-geometry intakes. This aircraft was borrowed from the U. S. Navy for use in the SST approach control studies.

The NB-52B Stratofortress– The NASA NB-52B (fig. 11) is a modified B-52B Stratofortress, a strategic bomber with a high, swept wing and eight engines (ref. 2). This aircraft was modified to carry and

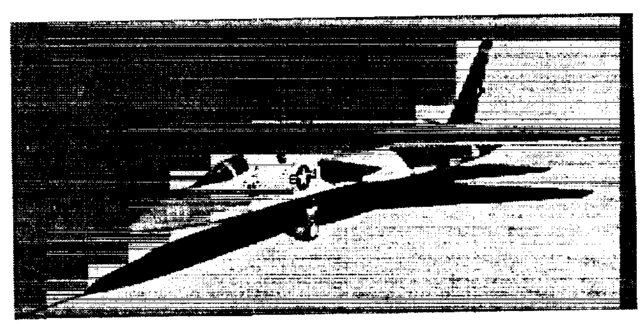


Figure 10. The NASA A-5A Vigilante aircraft.

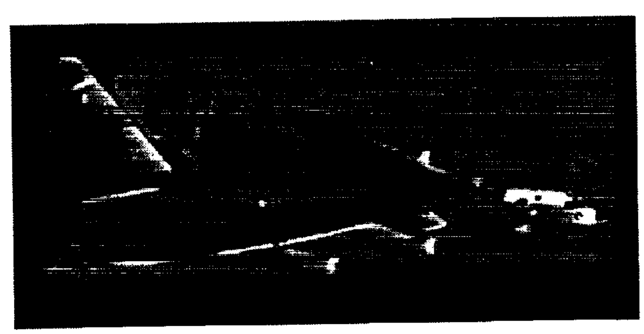


Figure 11. The NASA NB-52B Stratofortress aircraft.

launch the X-15. It has an inboard pylon on the right wing and a large notch in the inboard flap. Dryden acquired this airplane in 1959 and it is still in use.

The F-111A– The F-111A (fig. 12) is a supersonic sweep-wing, twin-engine tactical bomber. The aircraft belonged to the USAF and was flown by NASA and air force pilots in support of the shuttle program.

The CV-990– The NASA CV-990 (fig. 13) was a four-engine transport aircraft that was used in several transport flying qualities investigations in the 1960s. This aircraft was then converted to an airborne observatory by NASA.

The PA-30 Twin Comanche– The NASA PA-30 (fig. 14) is an extensively modified PA-30 Twin Comanche, a twin-engine, low-wing, four-seat general aviation airplane. The modifications include a complete flight-test instrumentation system and an uplink–downlink system for telemetering pilot commands and aircraft response, for the emulation of remotely piloted research vehicles (ref. 10). This airplane was acquired by DFRF in 1967 and is still in use.

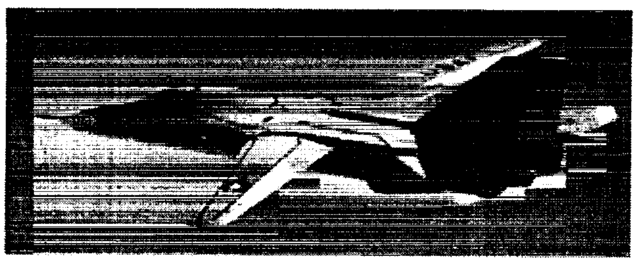


Figure 12. An F-111A aircraft.

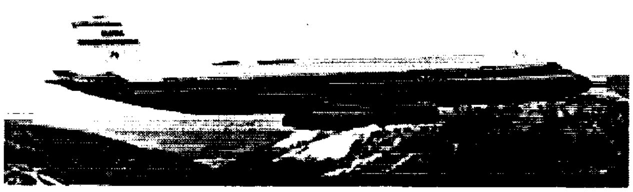


Figure 13. The NASA CV-990 aircraft.

Figure 14. The NASA PA-30 Twin Comanche aircraft.

The YF-12 Blackbird– The NASA YF-12 Blackbird (fig. 15) was a twin-engine, Mach-3 interceptor aircraft. Two models, the YF-12A and the YF-12C (visibly differing mainly by the length of the chine), were used for supersonic research in propulsion, structures, and aerodynamic heating (ref. 15). These airplanes were operated at DFRF from 1969 to 1979.

The F-15 Eagle– The NASA F-15 Eagle (fig. 16) is a twin-engine, Mach-2 air superiority fighter. This aircraft, used in propulsion research, has an advanced digital engine control system.

CHRONOLOGY OF IN-FLIGHT SIMULATION AT DRYDEN FLIGHT RESEARCH FACILITY

Low Lift-to-Drag Ratio Approach and Landing

In the late 1950s, the F-104A Starfighter aircraft was used in a generic study to investigate low-L/D approach and landing techniques (refs. 12, 13, and 15).

Figure 15. A YF-12 aircraft.

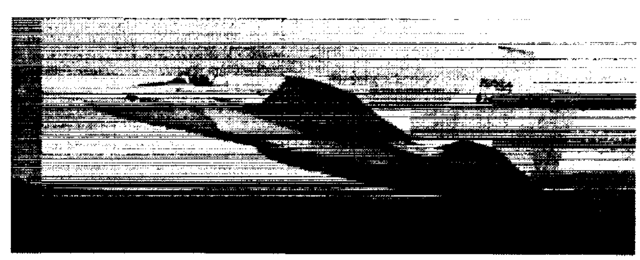


Figure 16. The NASA F-15 Eagle aircraft.

By suitably scheduling thrust- and drag-producing devices, a maximum L/D as low as 2.8 and a wing loading of about 75 lb/ft^2 was obtained.

A similar generic study was undertaken with the F-102A Delta Dagger, with maximum L/Ds of 3.8 at a wing loading of 35 lb/ft^2. Circular landing patterns were used by the pilots and a 270°-approach was preferred by the pilots in both studies, as this enabled them to establish a desired initial orientation before landing. An L/D of 3.5 presented no problem in the F-104A approach and landing. Lower L/Ds, down to 2.8, caused no problem arriving at the touchdown point. However in this latter case, it was difficult to judge the factors controlling the flare to achieve acceptable vertical velocity at touchdown. No such difficulty was noticed with the F-102A Delta Dagger because of its lower wing loading and the resulting increased float time.

X-15 Approach and Landing

Before the X-15 aircraft was flown, the F-104A Starfighter and F-102A Delta Dagger were used to simulate it in the landing and approach phase (refs. 15–18). The X-15 was a low-L/D vehicle (fig. 17) that could only be landed dead stick at fairly high speeds, so it was important to establish the landing pattern and to train the pilots in the proper procedure. This study was done to determine an optimal landing technique for the X-15 and to obtain information applicable to other reentry vehicles. Several F-104A Starfighters were used to evaluate circular and straight-in approach procedures under simulated X-15 mission conditions. The experienced test pilots who participated in this study preferred the flexibility of the circular pattern. One reason for this preference is that turn rate can be used as an energy management device, making precise landings easier (ref. 19). However, there was little difference between the two landing techniques in regard to final control of the touchdown conditions. Experience with the F-104 aircraft indicated that an L/D of approximately 2.5 in the flare represented a practical lower limit for piloted flared landings and that an aircraft with a lower maximum L/D could not be landed reliably. The F-104 simulation also indicated the desirability of extra airspeed during approach and landing, providing better control capability throughout and giving the pilot an extra g margin during the flare.

Figure 17. The X-15 experimental rocket vehicle.

The F-102A Delta Dagger, modified with large speed brakes, was also used at this time in a performance simulation of the X-15 in approach and landing. The F-104s were also used later for pilot training for the X-15 and the lifting bodies (refs. 18 and 20).

Investigation of X-15 Roll-Damper-Off Controllability and Motion Feedback

Early in the X-15 program, even before the first flight, it was determined that the aircraft was unstable with roll damper off (refs. 16, 17, and 21). An unconventional piloting technique known as the sideslip rate ($\dot{\beta}$) technique was developed and the instability investigated in the variable-stability F-100C and NT-33A aircraft. The $\dot{\beta}$ technique used small, discrete pulses to control the aircraft.

Another element in the problem was identified as motion feedback. The variable-stability F-100C and the NT-33A aircraft were also used to assess the X-15 motion feedback phenomenon in the late 1950s and early 1960s (refs. 16, 17, and 22). The aircraft motion was fed back into the stick through the pilot's arm. The pilot attempted to hold the stick fixed but the airplane motions caused the pilot to inadvertently apply small control inputs and increase the amplitude of the oscillation. When the pilot let go of the stick the oscillations damped out. When the pilot attempted to apply conventional corrective control the amplitude again increased. Although use of the X-15 side stick alleviated this problem somewhat, it was necessary to develop the unconventional $\dot{\beta}$ technique to enable the pilot to control and damp this motion effectively. A fixed-base simulation was initially used to examine the problem. However, the lack of motion and outside visual cues gave an overly optimistic indication of controllability compared to flight (ref. 18).

NT-33A Simulation of the X-15 Reentry

The NT-33A aircraft was used to simulate the reentry characteristics of the X-15 in 1960 (refs. 5, 23, and 24). The NT-33A was configured to match the dynamics of the X-15 and special instrument displays simulating those of the X-15 were also used, as was a side stick controller. The evaluation pilot took over control of the NT-33A aircraft in a zero g environment, accomplished the initial rotation of the airplane to the proper angle of attack, and subsequently made an instrument reentry, with the gradual build up of normal acceleration occurring just as it would in the X-15. This build up of normal acceleration was accomplished by rolling the plane. The technique worked because the evaluation pilot was flying "under the hood" using instruments only. Roll-damper on and roll-damper off configurations were evaluated, since ground simulation had indicated that the X-15 with roll-damper off was somewhat unstable. That instability and the pilot's ability to compensate for it were verified in this study.

F-104 Reaction Control System Program

An instrumented YF-104A aircraft had a reaction control system installed and tested in 1960 (refs. 16 and 25). This reaction control system program was done to obtain flight experience with jet reaction controls at low dynamic pressures prior to testing the X-15 aircraft in that region and to determine the handling qualities of the airplane at low dynamic pressures. This YF-104A is on display in the National Air and Space Museum in Washington, DC, near the X-15 that it simulated.

F5D Skylancer Assessment of Off-the-Pad Escape and Landing Maneuvers for a Hypersonic Glider

The F5D Skylancer was used in an early 1960s performance simulation to assess off-the-pad escape and landing maneuvers for the X-20 DynaSoar, a hypersonic glider (refs. 16 and 26). The F5D was used because of its low L/D and the resemblance of its planform to that of the X-20 DynaSoar. The proposed hypersonic glider would have been launched vertically from a large booster rocket and landed unpowered. Flight crew safety concerns in the event of a booster malfunction on the pad or shortly after launch led to the proposal of an auxiliary booster to pull the glider away from the danger area so that the pilot could assume control and land nearby. However, such hypersonic gliders had low L/D and were landed unpowered. In addition, thermal-structural consideration led, then as now, to minimally sized windows, limiting the pilot's field of view.

The simulated escape maneuvers were entered from a high-speed run approximately 1,000 ft above ground level. The pilot pulled up vertically and cut power, extending the speed brakes. This simulated the auxiliary-booster-rocket burnout. The approach and landing maneuvers examined were 360°-spiral and straight-in approaches. A blue–amber system was used to restrict the visibility, with two different window configuration being examined. (The blue–amber system uses a transparent blue visor with a transparent amber plastic lining of the canopy. The pilot can see the cockpit instruments through the blue visor but cannot see out of the canopy because amber is the complementary color.)

The simulated escape maneuvers were acceptable to the pilots, with good control. The circular pattern was again preferred and flare control was not affected by the restricted visibility. The visibility restriction did not interfere with navigation capability, although it did adversely affect portions of the escape maneuvers and landing approaches, particularly in the location of the high-key point.

F-102A Delta Dagger Simulation of Hypersonic Glider Landing-Approach

The F-102A Delta Dagger aircraft, like the F5D Skylancer, was used in landing-approach simulations of a hypersonic glider (X-20 DynaSoar) in the early 1960s (ref. 16). The same circular and straight-in approach and landing patterns were examined and the same conclusion reached. Pilots thought that circular patterns allowed more control in positioning the aircraft relative to the runway and in the flare.

A-5A Vigilante Assessment of Supersonic Aircraft in Traffic

An A-5A Vigilante was also used in 1963 to determine if there were problems inherent to operating an SST in a dense air traffic network (refs. 21 and 39). This was first explored at Edwards, with light traffic, and supersonic approaches were eventually flown into the terminal approach and departure control zones at Los Angeles International Airport. The only piloting problems associated with flying the supersonic transport profile appeared to be minor, limited primarily to speed and altitude fluctuation during the high-speed–high-altitude portion of the profile and overshoot tendencies during level-offs from steep portions of the climb. Integrating the test aircraft used to simulate a supersonic transport resulted in only minor compatibility problems with the air traffic control system.

T-33A Shooting Star Study of Restricted Fields of View For Approach and Landing

In the mid-1960s a T-33A Shooting Star aircraft was used to determine the relationship between the pilot's field of view and the performance of the landing task (ref. 27). The field of view was reduced from unrestricted to a minimum of 5.7° horizontal and 30° vertical, using a blue–amber system. The pilot's task was to fly a 180°-power-on pattern and final approach and to land the aircraft on a predetermined point on the runway. In addition, 360°-power-off overhead and straight-in approaches were performed by one pilot. Data taken included pilot comments and touchdown error.

Performance of the precision landing task, as measured by the touchdown error, was not affected by the reduced field of view. However, pilot comments indicated that the task became increasingly difficult with decreasing field of view (fig. 18).

F-104 Investigations of Approach and Landing Visibility

The F-104 aircraft have been used for many investigations into visibility requirements for approach and landing for low-L/D aircraft (ref. 28). The first, in the early 1960s, used an F-104B aircraft with an indirect viewing system that had two wide-angle overlapping periscopes with stereoscopic vision, for conventional and low-L/D landings (ref. 29). The periscopes were mounted on the canopy bow between the front and rear cockpits (fig. 19) and the image was shown to the evaluation pilot in the rear seat. This system showed safe and acceptable performance in all phases of daylight flight. When the horizon was in the field of view, aircraft attitude sensing with the optics was satisfactory about all axes except pitch attitude in climbing flight. This degraded pitch-attitude sensing was caused by the poor resolution at the bottom of the field and the lack of view to the sides. However, this system had such large light loss and degraded resolution that it was not usable for night operations. It was also found that more view directly to the side was needed to perform circling approaches.

The second study, with the same setup, examined the use of the stereoscopic periscope system in lifting body approaches and landings (ref. 30). Three approach techniques (circling approach, straight-in approach, and a three-turn multiple-aim-point approach) had been proposed for lifting body approaches. The previous F-104B study had determined that the circling approach required side vision which the periscope system did not provide, so the two approach techniques requiring only forward vision were added to the assessment.

The previous F-104B program had left some doubt about the system's suitability for low-L/D approaches and landings because of the effects of exaggerated stereopsis at or near the ground. To solve this problem, a radar altimeter was also installed and pressure altitude, radar altitude, radar altitude rate, and indicated airspeed were inserted into the field of view of one of the periscopes. However, this early attempt at a head-up display (HUD) was unsuccessful, as the pilots found the information unreadable or unusable. Interestingly enough, pilots, with their excellent uncorrected

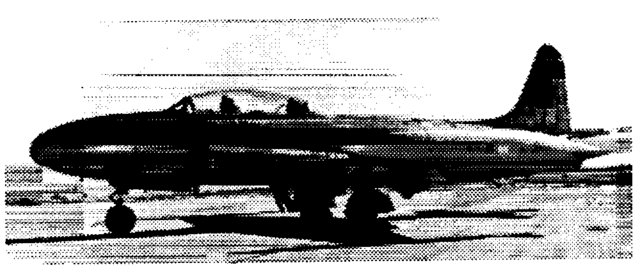


Figure 18. The NASA T-33A aircraft.

Figure 19. The NASA F-104B Starfighter aircraft with periscopes mounted on canopy bow.

vision, found this periscope system tiring and difficult to use while non-pilots who wore glasses did not have such problems. As in the study of conventional approaches and landings, the optical system provided adequate visual information for the flare and landing tasks and landing performance characteristics comparable to those obtained with normal vision. The exaggerated stereopsis played only a minimal roll in the high-speed landings, compared to the slower landings in the first study of this system.

The third F-104 limited visibility study, flown in the 1960s, involved masking the forward view, so the pilot had to rely on the field of view from side windows to land (ref. 31). An appreciable amount of the forward field of view could be obscured before the landing performance suffered markedly.

In 1990, the fourth study used stencil board to mask the front cockpit field of view of the TF-104G (ref. 28). This technique was also used in the third study. A number of windows, selected to match those proposed for the National AeroSpace Plane (NASP), were examined using straight-in approaches. In agreement with the earlier results, it was found that the pilot could land the plane with a fairly limited field of view. Unlike the earlier studies no circling approaches were examined, since it was assumed that some type of external guidance would deliver the airplane to the high-key position.

This TF-104G is currently being measured and instrumented for the installation of a folded-mirror optical viewing system which has been proposed for the NASP. This monoptic system for low-L/D approaches will be tested in the same manner as was the stereoptic system, with low-L/D approaches and precision landings.

NT-33A Simulation of M2-F2 Pilot Induced Oscillation

In 1965 the NT-33A aircraft was used to examine lateral–directional handling qualities of a variety of flight characteristics for the reentry mission (ref. 32). One set of configurations matched the M2-F2 lifting body (fig. 20) being tested at DFRF at the time. This simulation program found a coupled roll-spiral PIO (or lateral phugoid) which later manifested itself in the M2-F2 (refs. 21 and 33). The M2-F2 PIO was anticipated because it had been seen in the NT-33A simulation. This coupled roll-spiral PIO had been encountered in up-and-away flight twice and had posed no problem. When this PIO was encountered on final approach it was quite severe and led to a serious accident.

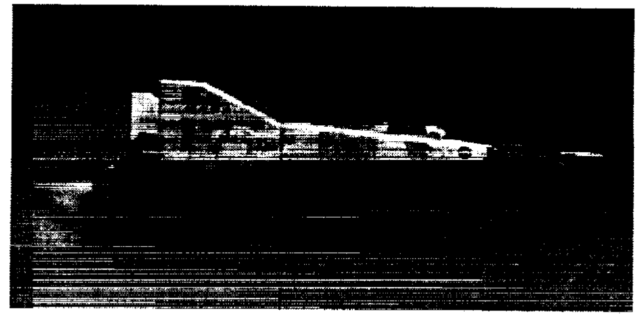


Figure 20. The NASA M2-F2 lifting body.

Lunar Lander Research Vehicle

The Lunar Lander Research Vehicles (LLRVs) (fig. 21), a program of the mid-1960s, were initially procured to examine the problems associated with lunar landing (refs. 21, 34, and 35). Lift and attitude control rockets were used during the landing simulations but the jet engine of the vehicle was used to lift and translate the craft to the simulation starting point. This led unavoidably to the examination of low dynamic pressure vertical take-off and landing flight. This jet engine was also used to counter 5/6 of the weight of the vehicle, simulating the lunar gravitational acceleration. The variable-stability control system permitted the examination of attitude command and of rate command with on–off control acceleration and proportional acceleration. Pilots discovered that attitude command was easier to fly than rate command and that satisfactory control was more easily achieved in rate command with on–off control acceleration than with proportional control.

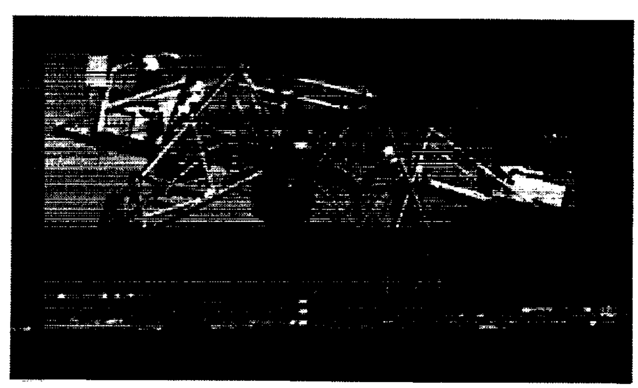


Figure 21. The NASA Lunar Lander Research Vehicle.

The visual, motion, and audio cues made the simulation highly effective. The LLRVs were so successful at simulating lunar landings that they were transferred to the space program (ref. 21) and used for astronaut training, renamed Lunar Lander Training Vehicles, type A or LLTV-A. Three more derivative vehicles, the LLTV-Bs, were later acquired by the space program.

General Purpose Airborne Simulator Simulation of Supersonic Cruise

The Valkyrie GPAS was programmed to simulate the Mach-3 XB-70 aircraft (fig. 22) as part of the initial testing of the aircraft in the mid-1960s (refs. 36 and 37). After this testing, the simulation was used as a pilot training tool in the XB-70 program and was also proposed for evaluation of the cruise regime of proposed SSTs (ref. 38). The F100C aircraft was also used to study SST flying qualities (ref. 21). The F5D Skylancer was used to establish minimum speed criteria for the proposed SST (ref. 15).

General Purpose Airborne Simulator Investigation of Motion and Visual Cues

An interesting part of the mid-1960s initial testing of the GPAS system was a study of motion and visual cues (ref. 37). The effects of mismatched cues on observed handling qualities were studied by varying yaw rate and lateral acceleration at the pilot's location, while keeping constant the lateral–directional dynamics displayed on the pilot's instruments. This experiment showed pilot sensitivity to directional motion cues to be different for the simulation of two XB-70 flight conditions. Motion cue effects were determined using consecutive evaluation of moving-and fixed-base configurations in flight.

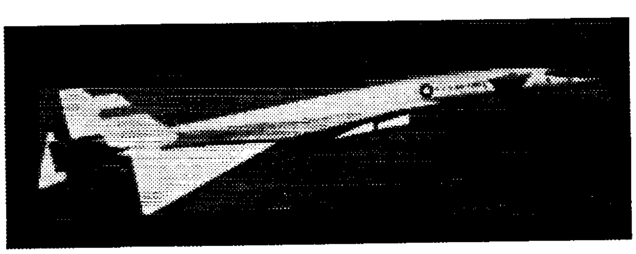


Figure 22. The XB-70 Valkyrie aircraft.

The second area investigated in this study was the measurement and description of simulation fidelity. In-flight frequency response measurements of the model-following system were taken to examine model-following fidelity for directly matched variables such as sideslip and roll rate as well as uncontrolled parameters such as lateral acceleration.

General Purpose Airborne Simulator Investigation of Roll Handling in Cruise and on Approach

The GPAS was used to evaluate roll handling for transport aircraft in both cruise and approach in the mid-1960s (refs. 40 and 41). In cruise, maximum roll-control angular acceleration, maximum available roll rate, roll time constant, and bank-angle change in a given time were all found to be effective roll-criteria parameters and the criteria developed in this program agreed well with previously proposed roll criteria. In approach, maximum roll rate, roll time constant, and wheel characteristics were varied.

General Purpose Airborne Simulator Simulation of the HL-10 Lifting Body

In 1967 the GPAS was used to investigate the longitudinal flying qualities of the HL-10 lifting body (ref. 42). Two flights were flown, but the simulation was not entirely satisfactory because of limitations in the closed-loop response of the GPAS (ref. 6).

General Purpose Airborne Simulator Investigation of Ride Qualities– In the early 1970s the GPAS was used to investigate ride qualities, particularly in turbulence. In the first study, subjects (naive non-pilots recruited from the DFRF support staff and junior engineers) evaluated the ride quality and any motion sickness symptoms that manifested themselves. This information was compared to the dynamic data collected during the various runs. From this data a number of ride quality rating models were proposed. The assessments were also compared to assessments made by a number of passengers on scheduled airliners.

In 1973-74 several ride smoothing flight-control systems (basic, command augmentation, and rate feedback) were evaluated in turbulence. These flight-control systems were designed to maintain good flying qualites while smoothing the ride, to the advantage of pilots and passengers (ref. 42). In the longitudinal axis command, augmentation systems reduced the normal acceleration response and the flightpath angle disturbances, compared to the basic and rate feedback systems, by greatly reducing the phugoid response. However, the calculated ride quality ratings showed only small improvements.

In the lateral–directional axes, significant reductions in roll rate, yaw rate, and lateral acceleration responses to turbulence were seen with a rate feedback system. The command augmentation systems were no better at reducing these responses; however, they did provide a significant reduction in bank angle and heading angle disturbances, which are of interest from a piloting standpoint. Some of the ride quality rating models indicated that these improvements modified the ride greatly while others showed no effects, depending on how greatly the lateral–directional variables were believed to affect the ride.

It was during a flight in support of this mission that the GPAS suffered an over-g condition and was retired. However, after new wings were installed, this aircraft was used as a testbed for a variety of experiments, including propulsion and boundary-layer control.

Shuttle Simulation Using Large, Low-L/D Vehicles

In support of the Space Shuttle Program, simulations of the shuttle using large, low-L/D vehicles, were undertaken in the late 1960s and 1970 using the NB-52B (fig. 11), an F-111A (fig. 12), and a CV-990 (fig. 13) (refs. 43 and 44). These large aircraft were configured for low L/D (the CV-990 had L/Ds of approximately 5 to 8, the NB-52B had L/Ds of about 3.3 to 8, and the F-111A had L/Ds from about 6.6 with the wings at 26° to about 3.7 with the wings at 72.5° and the gear down) and the engines shut down or throttled back sufficiently to produce power for necessary systems only.

The NB-52B and CV-990 aircraft were initially used to evaluate the feasibility of landing such vehicles. Once it was determined that large, low-L/D aircraft could be landed visually, the programs were expanded to examine instrument flight rules (IFR) approaches and landings with the NB-52B, instrument landing system (ILS) approaches and landings with the F-111A, and ground-controlled approaches (GCA) and landings with the F-104 aircraft. Again, a circling approach was found to provide the best energy management and control of the touchdown point. A YF-12 aircraft (fig. 15) was also used as part of this effort to develop baseline flying qualities data for large, low-L/D aircraft in the approach and landing.

PA-30 Emulation of Remotely Piloted Research Vehicles

The PA-30 aircraft (fig. 14) was used in the early 1970s in a remotely piloted mode (refs. 8 and 45) to practice piloting techniques for a variety of unmanned remotely piloted research vehicles (RPRV), including the 3/8-scale F-15 RPRV, an unpowered model used in spin testing; the Drone for AeroStructural Testing (DAST) aircraft, a modified Firebee drone used to examine aeroelasticity; and the Highly Maneuverable Aircraft Technology (HiMAT) aircraft, an aerodynamically advanced supersonic RPRV.

The PA-30, a low-wing, twin-engine general aviation airplane, provided training and currency for the exacting task of landing the RPRVs, and some currency in the ground cockpit. In addition, a variety of cameras and displays were tested to determine effective ways of presenting information to the pilot of a remotely piloted aircraft.

The PA-30 aircraft was equipped with a television camera and the picture was down-linked to the ground and shown to the pilot. The PA-30 was later used to research visual requirements for the remote piloting task, with various focal lengths and fields of view being examined. Stereoptic presentations were also examined.

Total In-Flight Simulator Investigation of Shuttle Pilot-Induced Oscillation

On October 26, 1977 the Space Shuttle Enterprise (fig. 23) exhibited a fully-developed PIO in both the roll and pitch axes during a landing on the paved runway during the approach and landing test program. As a result, in 1978 the Total In-Flight Simulator (TIFS) aircraft was used in a simulation program to discover and confirm the reasons for this PIO (ref. 46).

Analysis indicated that PIO was caused by several factors, among them time delay in the FCS and the position of the pilot relative to the center of rotation (ref. 46). The pilot's position masked the normal motion cues, since the pilot was somewhat behind

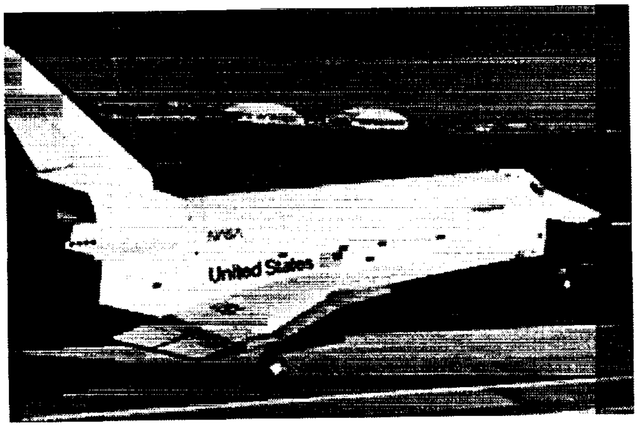


Figure 23. The Space Shuttle Enterprise about to touch down on the paved runway.

the center of rotation. Surface rate limiting also contributed to the apparent time delay. This simulation confirmed the effects of these factors.

F-8 Digital-Fly-By-Wire Evaluation of Effects of Time Delay on Handling Qualities

Immediately following the TIFS investigation of the shuttle PIO, the F-8 DFBW was used in a test program to study the effects of time delays in a digital control system like that of the shuttle and to provide more insight into the shuttle approach and landing experience (refs. 47 and 48). Transport delays were inserted into the roll and pitch axes and evaluated with formation flying and precision landing approaches (straight in and offset) at idle power, simulating the low-L/D approach typical of the Space Shuttle. In the pitch axis three different control modes were examined; stability augmentation, command augmentation, and no augmentation. The addition of time delay markedly affected the pilot's ability to control the airplane, to the point that the pilot scraped the tail of the plane on the runway during one go-around.

Formation flight was much less sensitive to the effects of time delay than was the approach task. Offset landing (where the pilot could not set up the approach but had to fly the plane more aggressively) was approximately twice as sensitive to time delay as was the straight-in approach. Furthermore, the ratings in pitch were most strongly affected by the task and were only slightly affected by changes in control system augmentation mode.

Total In-Flight Simulator Investigation of Shuttle Pilot-Induced Oscillation Suppressor Filters

Further investigation of the shuttle PIO led to the design of two candidate PIO suppression filters to control the problem. Flown in 1979, this TIFS investigation examined two PIO suppression filters that were proposed as an addition to the shuttle FCS (ref. 49). In addition, this program also examined some other modifications to the shuttle FCS, including feedforward of the pitch command and normal acceleration feedback. The effects of moving the pilot forward 100 ft were also investigated, although this was not proposed as a solution to the PIO problem. One of the two PIO suppressors evaluated in the TIFS program was implemented in the shuttle FCS prior to its first flight (ref. 50).

Pilot-Induced Oscillation Suppression Filter Assessment with the F-8 Digital Fly-By-Wire

The Space Shuttle PIO, caused in part by excessive time delay and the success of the PIO suppression filters devised to alleviate the problem, created an interest in the usefulness of PIO suppression filters in more conventional aircraft. In 1980 there was a program to evaluate the same types of filters in more conventional fighter-type aircraft using the F-8 DFBW (ref. 7). As previously described, the F-8 DFBW aircraft had already been used to evaluate the effects of time delay on digital FCSs so that the only addition required was the PIO suppression filters. The same two types of filters were examined, with a variety of breakpoints and filter slopes. The basic F-8 DFBW configuration was a good airplane with little time delay. Either a pure time delay or a first order lag was added to the FCS. The latter was used to simulate the cascading of filters in a poorly designed control system.

To provoke any possible PIO, two high-gain tasks were used. The first task, close-trail formation, involved flying just behind and below the F-104 chase plane. Pilots found that this task was somewhat artificial and not well defined. As a result of this assessment a more demanding task, probe-and-drogue refueling, was used in the second phase of the program. However, the results for the two tasks did not vary much.

The PIO suppression filters suppressed the PIOs in the configurations with added transport delay. They did not, however, help with the configurations with the first order lag.

NT-33A Pilot-Induced Oscillation Suppression Filters

In 1981 a simulation program was flown in the NT-33A aircraft to investigate PIO suppression filters in fighter-type aircraft (refs. 7, 51, and 52). A basically good configuration was selected as the baseline. To this baseline were added either time delay or lag pre-filtering in the longitudinal axis, similar to the F-8 DFBW PIO suppression filter study, and the same two PIO suppression filters were examined. In this study, the task was a precision offset landing.

The results of this and the F-8 DFBW experiments matched the shuttle program results, indicating that PIO suppression filters worked well for fighter-type aircraft as well. The PIO suppression filter greatly reduced PIOs, even with excessive time delay that led to serious PIOs in configurations without the filter. Already good flying qualities were not degraded by the filters. However, in the NT-33A study, as in the F-8 DFBW studies, the filters made configurations with lag pre-filtering worse, indicating that poor system design could not be compensated for with the PIO suppression filters.

F-8 Digital Fly-By-Wire Investigation of Nonlinear Control Algorithms

In the early 1980s the F-8 DFBW was used to investigate active, nonlinear flight-control techniques and handling qualities in a cooperative program with the Royal Aircraft Establishment (ref. 53). The evaluation was accomplished using the RAV mode.

The purpose of the study was two-fold, with the first goal being to establish whether a variable-gain controller could offer improved control performance over a linear baseline pitch-rate command system and whether any adverse handling problems would be introduced by the rapidly varying gain. The second goal was to investigate the effects of a nonlinear command pre-filter. The nonlinear pre-filter was designed to provide a small overshoot on the pitch rate and a relatively slow buildup of normal acceleration for small commands and to increase the pitch-rate overshoot and normal acceleration response for large commands. This was accomplished by varying the lead time constant of the pre-filter.

Distant tracking and close tracking were the two typical fighter tasks evaluated. The nonlinear pitch-rate command system worked well in the distant-tracking task; however, it was discovered that different responses are preferred for the two different tasks. Low-overshoot pitch-rate responses are preferred in the distant-tracking task and high-overshoot pitch-rate responses are preferred in the close-tracking task.

Nothing conclusive was learned about the variable adaptive, lead pre-filter time constant because the range of pre-filter time constants was not sufficiently related to the augmented dynamics. The F-8 DFBW aircraft, with its versatile FCS, was also used at this time in a brief, undocumented study of roll mode time constant and roll ratcheting.

Total In-Flight Simulator Investigation into Pitch Rate Command Systems in the Flared Landing Task

In 1983 an extensive TIFS investigation into pitch rate commands in the flared landing task was undertaken (refs. 56 and 57). This study evaluated pitch-rate feedback with proportional and integral forward paths, rate command design, lead–lag pre-filters, superaugmentation, superaugmentation with lead–lag pre-filters, neutral static stability, and angle of attack and pitch-rate feedback required for level 1 conventional aircraft response. The aircraft configurations evaluated were a matrix constructed from seven aerodynamic models (three stable aircraft with different values of $1/\tau_{\theta_2}$, two neutrally stable aircraft with different values of $1/\tau_{\theta_2}$, a shuttle-like vehicle, and a shuttle-like vehicle with canards) and eight pitch axis FCSs (two proportional plus integrated pitch-rate feedback systems with different undamped short-period frequencies ($\omega_{n_{sp}}$), superaugmented, conventionally augmented, three shuttle FCS variants, and one shuttle FCS variant with a time delay).

Results from this study included findings that current integral-proportional pitch-rate FCSs provided good attitude control, which is required for good performance in the flared landing task. In addition, the pilot needs cues to control flightpath precisely in the landing flare. These cues may come from pilot acceleration, stick deflections and forces, initial aircraft response, and longer term aircraft response. In addition, many techniques can be used to provide level 1 performance.

Interestingly, this study discovered that classical predictive criteria did not provide adequate prediction for the flared landing task, although a time-domain predictive criterion developed from this experiment did work well.

Total In-Flight Simulator Validation of the X-29 Control System

The TIFS was used in 1984 to examine the X-29 control system, with particular attention to power approach (ref. 58). The X-29, with its forward-swept wing (fig. 24), is a statically unstable fly-by-wire airplane with a digital primary FCS, a digital backup FCS, and an analog backup FCS. This vehicle has a canard and a strake flap in addition to the full-span flaperon and rudder. The canard, strake flap, and flaperon are used for pitch control; the flaperon alone for roll control. Ground simulation had raised questions about the flying qualities of the X-29 in power approach, with some indication that the lateral–directional gains and stick gearings might be unsatisfactory. A three-phase program was undertaken to examine these issues.

In the first phase, the originally proposed gains and stick gearing were examined in up-and-away and in power approach in the primary and both backup modes. Numerous PIOs led to reduction of the lateral–directional gains and the stick gearing in the primary mode and in the digital backup mode. The analog backup mode initially received only a limited evaluation because of a simulation anomaly, but the gains were modified and a corrected analog backup mode was evaluated. This corrected mode also demonstrated a number of PIOs, but because of the limited data, no changes were made in this mode. The primary and digital backup modes were, however, modified with reduced gains and stick gearing.

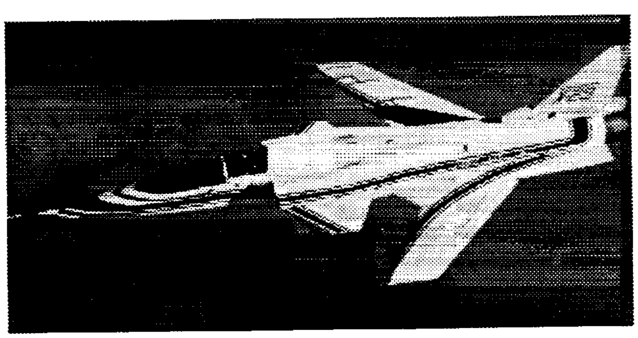


Figure 24. The forward-swept wing X-29 aircraft.

Phase two of this study was a quick-look program that examined the design changes that resulted from phase one. Phase three, flown shortly before the first flight of the X-29, provided one last evaluation of the control laws in power approach, familiarization with the first-flight profile for the pilot and the control room personnel, and evaluation of selected emergency landing modes. The primary concern in this phase was the lateral PIO in the analog backup mode, which raised a safety-of-flight question. In this phase, the flying qualities in all modes were found to be adequate for the first flight. The primary and digital backup modes, with their gains determined in previous testing, were found to exhibit level 1 and 2 handling qualities and the analog backup mode exhibited levels 1 to 3 handling qualities.

The X-29 aircraft was later flown at altitude in the analog backup mode to examine the lateral PIO seen in the TIFS study. Precision tasks, including bank angle captures and formation flight, were used to provoke any PIO. However, no lateral PIO tendencies were seen. This difference between the TIFS and the aircraft was attributed to errors in the predicted mathematical model of the X-29 and to the model-following techniques used to quicken the TIFS response, allowing this large airplane to fly like a fighter.

Total In-Flight Simulator Investigation of Proposed Shuttle Flight-Control System Modification

After the successful PIO suppressor study, another TIFS study was done in 1985 to examine further possible changes to the orbiter FCS (refs. 54 and 55). In particular, a shaped pitch-rate feedback system, a command pre-filter and pure pitch-rate feedback equivalent system, and a C^* feedback system were compared to the baseline shuttle system. Additionally, reducing time delay in the FCS by moving the body bending filters from the command path to the feedback path was examined.

Although the addition of canards to the orbiter was not seriously contemplated, the use of canards was evaluated with the baseline and modified FCSs. Canards would have given sufficient control of the center of rotation so that the problems caused by pilot location would have been greatly reduced.

Learjet Flying Qualities Research

In the mid-1980s the first variable-stability Learjet was used for a limited in-flight simulation program that examined the effects of feel system dynamics on aircraft lateral handling qualities in the approach and landing task (ref. 59). This study was sparked by the results of a brief study in the NT-33A aircraft (ref. 59). In this Learjet study, two feel systems, one fast and one slow, were examined. The flight-control configurations had two possible transport time delays, designed so that the equivalent time delay for the feel system and FCS combined were the same in each case. A baseline configuration with minimum overall time delay was also included. The tasks were bank angle captures and lateral-offset spot landings.

This study showed that the location of the time delay is important and that the feel system should be regarded as a separate dynamic element. Large overall time delay could be tolerated if a significant portion of the delay resided in the feel system. However, the same amount of overall time delay was unacceptable to the pilot if much of the delay was transport time delay downstream of the feel system. Additionally, this study indicated that the allowable time delay in the roll axis is a function of initial acceleration rate or "jerk."

The first variable-stability Learjet has been used as a training tool at DFRF since 1983. Engineers are exposed to a training syllabus based on that used by the Air Force and Navy Test Pilot Schools (ref. 11). All axes and modes are examined and stable, neutrally stable, and unstable configurations are flown. Time delays and feel system dynamics can also be varied. This aircraft has also been used by test pilots to review flying qualities areas.

NT-33A Investigation of Feel-System Characteristics on Roll Dynamics

In the late 1980s an investigation of the influence of lateral feel-system characteristics on fighter aircraft roll axis flying qualities was done with the NT-33A (ref. 3), partly in response to the Learjet study of feel-system dynamics. This extensive study examined power approach, visual landing, and up-and-away tasks including formation, gun tracking, and computer-generated compensatory attitude tracking tasks displayed on the HUD. Experimental variations included the feel system frequency, force-deflection gradient, control system command type (force or position input command), aircraft roll mode time constant, control system pre-filter frequency, and control system delay. The investigation was undertaken to determine how the feel system and the FCS interact and how the pilot assesses each.

The feel system is not equivalent to analogous control system elements in its influence on flying qualities. This led to the conclusion that flying qualities criteria should treat the feel system separately from the control system, since the feel system dynamics are apparent to the pilot and are not hidden in the total dynamics.

Investigations of Flightpath Control Using Throttles Only

In 1989 an airliner accident in which hydraulic power failed completely and differential thrust was used for flightpath control led to an investigation of the use of throttles for emergency flight control (ref. 60). In addition to fixed- and moving-base ground simulations, this investigation included a cursory flight simulation program using the first variable-stability Learjet, the F-15, and the PA-30 aircraft. In twenty minutes of flight using throttles only, the Learjet demonstrated some control capability, with heading and altitude maintained within 500 ft. It showed good roll controllability with differential thrust and poor pitch control, with the phugoid being difficult to damp with throttle inputs.

The PA-30, a low-wing, twin-engine four-seat general aviation airplane, was difficult to control in all axes with thrust only. Gross control of the PA-30 was possible but landing on a runway would have been difficult.

The F-15, a twin-engine air superiority fighter, demonstrated good roll response and pitch response to throttle control. The F-15 rolled and banked well with throttle control only and a heading could also be held well. Altitude could be held within 100 ft at airspeeds below 200 kn, though phugoid damping was difficult.

These three experiments indicated that it is feasible to develop a control system for a large transport that would allow a safe return if hydraulic power were completely lost.

A more extensive investigation into the feasibility of thrust-only flightpath control used the second variable-stability Learjet in a six-flight program in the fall of 1991. Two different basic configurations, an

F-15-like fighter and a large transport, were examined. Apparent engine location was varied for the two configurations, although the actual engine characteristics (spool-up time, for example) could not be varied. This limited study determined that thrust-only flight-path control was extremely vunerable to turbulence and confirmed the necessity of special piloting techniques.

CONCLUDING REMARKS

There are two areas of major interest at the Dryden Flight Research Facility that simulation has addressed, which are landing fast, low-lift-to-drag ratio aircraft that cannot do go-rounds and pilot-induced oscillations in digital flight-control systems.

The first in-flight simulation program at the Dryden Flight Research Facility was an investigation of low-lift-to-drag ratio approach and landing characteristics, using the F-104 and the F-102A Delta Dagger aircraft. The most recent inflight simulation program here is an F-104 investigation into field of view requirements for the National AeroSpace Plane, a low-lift-to-drag ratio vehicle with limited visibility.

The X-15, the lifting bodies, X-20 Dynasoar, the shuttle, the National AeroSpace Plane–these low-lift-to-drag ratio airplanes land at high speeds and go-arounds are impossible. It has always been critical to get the landing pattern right before the flights. Inflight simulation has aided in the design of the pattern, the designation of high keys, approach angles, flare speeds, roundout altitudes, and touchdown speeds.

Structural and aerodynamic heating dictate small windows or remote viewing systems in hypersonic aircraft. The use of in-flight simulation answered questions on how small the windows could be, whether the remote viewing system needs to be stereoptic or monoptic, what resolution is required, what supplementary instrumentation is necessary and how to present this to the pilot, and a number of other display questions.

The interest of Dryden Flight Research Facility in aircraft with digital flight-control systems started around 1970 when the F-8 digital fly-by-wire program began. This aircraft, the first ever to be all-digital fly-by-wire, was used first as a demonstrator of the technology but it soon turned into a research tool examining digital flight-control system problems like roll ratcheting. Interest in pilot-induced oscillations has always been high in the fast, high-performance research aircraft like the X-15 and the lifting bodies, as evidenced in part by the studies previously mentioned.

These two threads came together dramatically on October 26, 1977, when the Space Shuttle Enterprise, making a precision landing on the main runway at Edwards Air Force Base, experienced a fully-developed multiple-axis pilot-induced oscillation. As soon as the dust settled, Dryden Flight Research Facility began to use its experience in the investigation of flight-test problems.

The data were analyzed and the first Total In-Flight Simulator program confirmed that the causes were known. The effects of time delays in digital flight-control systems were examined in the F-8 aircraft. The pilot-induced oscillation suppressor filters were developed and tested in a second Total In-Flight Simulator program. While these filters were proven to work well, Dryden Flight Research Facility continued to examine improvements to the flight-control system for approach and landing and these proposed changes were examined in another Total In-Flight Simulator program.

Dryden Flight Research Facility then moved on from the practical, fix the problem and get the aircraft flying again approach, to research into more general issues, examining pilot-induced oscillation filters in fighter-type aircraft with the F-8 digital fly-by-wire and the NT-33A.

The location of the time delay, either in the feel system or in the flight-control system, was examined quickly in the NT-33A aircraft, more thoroughly in the Learjet, and exhaustively in a major NT-33A study. Thus a seemingly isolated incident led first to a solution to the incident and then to a body of research into the root problems.

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